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CAPSULES FOR SURVEILLANCE OF SOME PLUM BROOK REACTOR STRUCTURAL MATERIALS

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INTRODUCTION

With the advent of the power operation of the NASA Plum Brook Reactor (PBR), surveillance irradiation programs on some structural metals were initiated. It is anticipated that these programs will continue for a period of years to allow exposures up to 10^{22} nvt for some of the metals. The objective of the program is to conduct surveillance irradiations on 3 metals used in the PBR core: Mallory 1000 (90% W, 6% Ni, 4% Cu), which is used as a gamma shield for a cryogenic experiment, 17-7 PH stainless steel, and beryllium.

Capsule experiments have been performed in other reactors to achieve certain objectives. These tests have included investigations on a variety of materials and testing conditions (e.g., ref. 1-5). Differences in test objectives and modus operandi necessitated certain unique features in the capsule designs for the surveillance tests being conducted for the PBR.

The Plum Brook Reactor Facility (PBRF) includes a 60-Mw testing reactor of the MTR type and a hot laboratory adjacent to the reactor building. The surveillance irradiation programs require removal of capsules from in-pile locations, transfer to the hot laboratory, disassembly, reassembly, and transfer back to the reactor. Certain capsule design criteria are required due to the nature of the PBRF. Three separate capsules with similar characteristics have been designed.

The present paper gives a brief description of the NASA Plum Brook Reactor Facility, discusses the criteria used for design of the capsules, and describes the capsules.

REACTOR FACILITY

The PBR, a 60-Mw test reactor, is light water-cooled and is of the MTR type with primary beryllium and secondary water reflectors. Suf-

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ficient concrete shielding is provided for the reactor shutdown period (fig. 1). A 70-ft circular pool of water, divided into quadrants, surrounding the concrete provides shielding for the power operation period. The water also provides shielding for transfer of experiments to the hot laboratory. The hot laboratory building, adjoining the reactor building, houses seven multikilocurie hot cells, cold and semicontaminated work areas, and storage areas. (More details of the PBRF and the hot laboratory are given in unpublished NASA data and ref. 6.)

A cutaway perspective of the reactor showing features such as test holes, pressure tank, transfer chute, and control mechanism is given in figure 2. A hatch at the top of the tank is provided for changing fuel elements and handling capsules in the pressure tank. Capsules are removed from the reflector positions, transferred via the fuel transfer chute to quadrant C, and transferred underwater to the hot laboratory, (figs. 1 and 2).

Views of the PBR and the test holes are shown in figure 3. Mallory 1000 metal, one of the surviellance materials, is used as a gamma shield in HB-2 for a cyrogenic irradiation experiment (ref. 7). The Mallory shield, located at the reactor end of HB-2, is exposed to a fast flux ($E > 1$ Mev) of about 10^{13} n/cm^2-sec when the reactor is at full power of 60 Mw. Beryllium, another surveillance material, is used as the reflector and also for core box structures. Spring material in the fuel elements and reflector pieces is 17-7 PH stainless steel, which is a third surveillance material.

Positions LA-5,7,9 and positions RA-2,7 will be used for the surveillance programs. Table 1 summarizes the programs.

TABLE 1. - SURVEILLANCE PROGRAMS FOR SOME PBR STRUCTURAL METALS*

Material	Use in PBR	Exposure flux n/cm^2-sec ($E > 1$ Mev)	Surveillance test hole	Surveillance flux n/cm^2-sec ($E > 1$ Mev)	Exposure number of reactor cycles**
Mallory 1000	Gamma shield HB-2	10^{13}	LA-5,7	1.5×10^{14} Max.	1,3,6,9,12, 15,18,21,24,27
Beryllium	Reflector	Varies	LA-9	1.3×10^{14} Max.	6,12,18,24, and yearly thereafter for 15 years
17-7 PH Stainless steel	Reflector and fuel elements	Varies	RA-2,7	3.7×10^{12} Max.	Yearly for 15 years

*Temperature of irradiation (~200° F) is considered environmental.

**A reactor cycle is about 10 days or 8.6×10^5 sec.

CAPSULE DESIGN

Surveillance programs on reactor structural metals require frequent removal and replacement of the test materials in the irradiation facility. Furthermore, it is desirable to monitor the actual exposure seen by the structural materials and to provide some degree of acceleration so that radiation effects may be predicted in advance of the actual exposure. Such a program involves a large number of test specimens with the capsule being loaded to maximum capacity.

For the surveillance program the following design criteria were used for the capsule:

(1) Insertion and removal of the specimen from the irradiation facility with minimum loss of time;

(2) Capability of containing a large number of specimens and of being readily disassembled for specimen removal without destroying the capsule;

(3) Removal and replacement of selected test specimens without complete disassembly of the capsule;

(4) Provisions for monitoring flux and temperature;

(5) Minimum alteration of reactor-primary-cooling-water hydraulics while not compromising reactor safety.

The following sections describe the features that meet these criteria.

Basic Assembly

The first capsule, designed for irradiation of Mallory 1000 metal (a tungsten - base alloy) in the LA pieces, set the pattern for subsequent capsules. When assembled this capsule forms a cylinder with a 2-in. diameter and a $38\frac{27}{32}$-in. length. The LA pieces (see fig. 3) have a beryllium plug that can be removed leaving a cavity with a $42\frac{3}{4}$-in. overall length. The upper $37\frac{1}{2}$ in. of this cavity has a $2\frac{3}{20}$-in. diameter below which the diameter is reduced to 2 in. for a $1\frac{1}{2}$-in. length, then to $1\frac{7}{8}$ in. for a $3\frac{3}{4}$-in. length. At the top of the cavity a circumferential groove has been machined on the inside of the beryllium piece at a point $2\frac{1}{4}$ in. below the top.

The capsule, shown in figure 4, consists of three major sumassemblies:

a top retention piece, a bottom retention piece and tie rods, and a test material subassembly. The test material may be encapsulated using either a single capsule segment (fig. 5) or multiple capsule segments (fig. 6).

Facility installation. - Three feactures of this capsule are designed specifically for installation in the lattice pieces. (The longitudinal cross section of the capsule in fig. 7 shows these features.)

(1) When installed in the reactor, the bottom retention piece (2-in. maximum diam.) is positioned in the 2-in. diameter by a 1.5-in.-long portion of the beryllium-lattice-piece cavity. The bottom of the capsule assembly (i.e., the bottom retention piece) is machined to a configuration that permits reactor primary cooling water to pass from the beryllium lattice piece into the reactor-primary-cooling-water exit system.

(2) Four balls installed and staked on the outside of the top-retention-piece body serve to lock the capsule in position. These balls engage the circumferential groove machined on the inside of the beryllium-lattice-piece cavity. In this position, the capsule assembly is locked so that it will not move up or down in the beryllium lattice piece. The capsule is centered in the lattice-piece cavity so that a 0.076-in. annulus for reactor primary cooling water is maintained between the lattice-piece cavity wall and the capsule-assembly wall (fig. 7, section D-D).

(3) A plunger installed in the top retention piece of the capsule is designed for handling the capsule remotely. Two circumferential grooves, machined on the outer surface near the bottom of the plunger, permit the balls to be retracted so that the capsule will move in or out of the beryllium lattice piece with ease. A coil spring, installed over the plunger and locked in position by Spir-O-Lox washers, positions the plunger so that the balls are in the locking position. A circumferential groove, machined at the upper end of the plunger, accommodates the grips of a remote handling tool. Pushing or pulling the plunger permits the balls to be retracted for insertion or removal of the capsule from the lattice piece.

These three features satisfy the first design criteria that the capsule fit the irradiation facility and be inserted and removed with ease.

Test specimen subassembly. - The capsule was designed to provide a 30-in. length for encapsulation of test specimens. This length corresponds to a region approximately 3 in. above and 3 in. below the fueled region of the PBR core.

Since it is desired to reuse the capsules, separate segments are provided in the 30-in. length (fig. 5). These segments, approximately 3 in. long are machined from 2-in. O.D. commercially pure aluminum (1100 grade) and are bored (1.5-in.O.D.) so that test specimens may be positioned internally. The ends of each segment are machined for interlocking fit with capsule segments being stacked, one on top of another, to make up the 30-in. test specimen section. A pin and mating hole scheme for each interlocking segment is used to prevent axial rotation of capsule segments.

The bottom retention piece and tie rods are further designed to hold the capsule segments together. The retention piece is machined to conform to the interlocking scheme of the capsule segments. Three aluminum (1100 grade) tie rods are installed in the bottom retention piece (fig. 4) and are locked in position by roll pins inserted across the diameter of the bottom retention piece. The tie rods are positioned inside the bore of the capsule segments and extend the full length of the capsule assembly. With this arrangement tensile specimens can be stacked, one on top of another, in the three sections formed by the capsule segment wall and two tie rods and in the center of the capsule segment cavity.

The top retention piece locks the capsule assembly as a unit (fig. 7). It consists of two interlocking sections designated as the top-retention-piece body and the tie-rod alinement section. The body and the alinement section are bolted together at the center. Alinement between these two sections is achieved by a roll pin in one interlock surface and a mating hole in the other. Longitudinal through holes serve as water channels and tie-rod penetrations. Three long-nosed screws, inserted through the side of the top retention piece, engage a hole through the tie rod, thus locking the capsule as a unit (see also fig. 4).

A 17-7 PH stainless-steel spring is installed over the bolt between the top-retention-piece body and the tie-rod alinement section. Spring action tightens the capsule assembly longitudinally and applies a load on the long-nosed tie screws.

These features satisfy the second design criteria that the capsule contain a large number of specimens and be readily disassembled without capsule loss.

<u>Test-specimen installation.</u> - While the test specimen loading scheme outlined in the previous section meets the design criteria for maximum loading, it does not permit easy removal of selected test specimens. In order to satisfy this further design requirement, the assembly shown in figure 5 was adopted.

Test specimens and aluminum tubes, which serve as sleeves for the capsule tie rods, are positioned in the capsule segment cavity. Specimen retention washers are placed on each end of the assembly. Snap-ring lock washers, placed in grooves on the ends of each sleeve, overlap both the specimen retention washer and the interlock surface of the capsule segment and lock the assembly.

Encapsulation of test specimens of different geometries is accomplished by modification of the specimen retention clip. For example, the specimen retention washer for flat bar specimens shown in figure 5 has clips brazed to the prongs.

For those conditions where a large number of test specimens are to be removed at the same time, the encapsulation is achieved by the assembly shown in figure 6. Here capsule segments and test specimens are stacked to form the desired length, and the subassembly tie is the same as that described above.

Spacers, machined in the same interlocking manner as the capsule segments, are employed between subassemblies, since clearance must be provided between the ends of sleeves of adjacent capsule segment subassemblies.

Using this loading scheme, encapsulation of thirty 1/4-inch diameter tensile specimens and thirty 1/8-inch diameter rod specimens, is achieved for the Mallory surveillance program.

Monitoring. - One of the basic criteria of any irradiation program is to ascertain the temperature and flux to which the test material is exposed. For metallic materials, the integrated neutron flux is the quantity desired.

Two techniques for flux monitoring were incorporated in the capsule assembly. One of these, built into the capsule itself, consists of holes drilled in the capsule segment wall. The other technique requires replacing the test specimen in the center of the specimen cavity with a flux monitor capsule. This flux monitor capsule consists of two slot-head cap screws, each designed to hold a single monitor wire, and an aluminum body (fig. 5). The cap screws are threaded and are positioned on opposite ends of the aluminum body.

Since the materials to be encapsulated in this program are high temperature materials, no temperature measurement was incorporated. The inlet and exit reactor primary cooling water ($\Delta T = 27^{\circ}$ F) is monitored during reactor operations and can be used for determining the thermal environment seen by the encapsulated test specimens.

Should temperature monitoring be desired, one approach would be to replace the central flux monitor capsule with a capsule designed to receive and contain buttons or slugs of materials whose melting points span the thermal range anticipated. A second approach to temperature monitoring would be to introduce thermocouples into the capsule assembly. The center of the capsule assembly is open to reactor primary coolant water flow and thermocouples could be installed without too much difficulty.

Heat-transfer analysis. - Heat-transfer calculations were performed for a capsule loaded with tungsten specimens. For these calculations using the TOSS program (ref. 8), the reactor full power (60 Mw) operating condition and the reactor shutdown condition were considered.

With the reactor at full power, the peak gamma heating value in the irradiation facility is 15 w/g. Using this value and the results of the flow test described later in this paper, the TOSS output showed the maximum specimen surface temperature under steady state conditions to be 209° F. The overall temperature rise of the reactor primary cooling water passing around and through the capsule assembly was calculated to be 24° F. These values are within the limits established for PBR heat transfer, that is, ~300° F surface temperature and 27° F temperature rise in the cooling water.

At reactor shutdown the gamma heat drops almost immediately to about 0.4 of the full power value. Thereafter a gradual reduction in heating rate takes place. For the analysis, step reduction in cooling water flow was assumed. The TOSS output showed a transient surface temperature rise to about 300° F, followed by a reduction to below 212° F, occurring over the 90-sec. time interval following reactor shutdown. The reactor shutdown schedule requires maintaining reactor tank pressure for a minimum of 5 min following reactor shutdown. Under this schedule the transient temperature approaches the maximum surface temperature permitted, but it still is acceptable.

The heat-transfer analysis was performed using the most severe (and in many cases unrealistic) conditions to be encountered. Tungsten introduces an additional severity in that high gamma heating values are encountered. It is significant to note that, under the assumed conditions of heat generation, permissible surface temperatures are not exceeded and the cooling water temperature rise is not excessive. Most structural materials will not encounter these conditions, and, hence, no heat-transfer problems are associated with the capsule assembly.

Stress analysis. - Stresses on the capsule result from (1) tensile loads due to specimen and capsule weight and reactor primary cooling water flowing through the capsule and (2) thermal stress due to differential heating of capsule components.

The capsule assembly is effectively suspended from the long-nosed tie screws in the upper retention piece. The capsule weight is concentrated on the bottom retention piece and distributed over the three tie rods. Figure 8 shows schematically the loading of the capsule assembly. For tensile stress analysis, one tie rod of the cross section shown in figure 8 was employed. It was assumed that all the capsule and the test specimen weight (12.15 lb) was applied to this rod. Furthermore, the load for reactor primary cooling water acting on a 1.5-in. diameter disk (71 lb) was added to the capsule and test specimen loads. The minimum cross section of a single tie rod (0.0242 in.²) was sufficient to hold this load with only slight elongation (0.011 in.).

Thermal stress analysis for a cylindrical pipe under the reactor temperature gradient conditions resulted in a negligible effect.

Thermal expansion calculations for the most severe temperature gradients were performed for all mating sections of the capsule assembly, the test specimen loading, and the capsule-beryllium piece mating areas. In no case was thermal expansion sufficient to cause binding and potential stress concentrations. The results of stress analysis show that the capsule assembly is sufficiently strong. As in the case of heat generation, the worst possible case was postulated for the analysis. Actual conditions should be less severe.

Modification of Basic Assembly

A second capsule was designed to encapsulate beryllium tensile and rod test specimens. This capsule was designed to be inserted in the same type of lattice piece (L-piece in fig. 3) as previously described for the basic capsule assembly. The pertinent features of this second capsule assembly are shown in figure 9. The basic design features of the second capsule are essentially the same as those previously described, and, hence, only the differences will be considered.

The second capsule assembly is designed with a single tie rod locked in the bottom retention piece and extending the full length of the capsule assembly. For locking in the top retention piece, a single long-nosed tie screw that extends across the top-retention-piece body is used.

Test specimen loading is confined to a single capsule segment using six-pronged specimen retention washers which fit over a single aluminum sleeve. Snap-ring lock washers positioned in grooves on the ends of the sleeve lock the assembly together. The prongs of the specimen retention washer are of sufficient length to engage the interlock surfaces of the capsule segment. To keep test specimens positioned with respect to rim segment flux monitor positions, 1/8-in. diameter holes are drilled in the ends of the tensile test specimen. Pins, brazed to the prongs of the specimen retention washer, engage the holes in the ends of the specimen and thus lock them in position. The prongs of the specimen retention washer are of sufficient length as to engage the capsule segment roll pin installed in the interlock surface. This permits a slight degree of rotation of test specimens relative to capsule rim segment flux monitor positions, but such rotation is not sufficient to be a problem.

Rod specimens are installed in the cavities between the tensile specimens and the aluminum sleeve. A snug fit is provided so that the rod specimens are locked in position. For capsule assembly, capsule segment spacer disks are employed between each capsule segment subassembly.

A third capsule, basically similar to the one just described, has been designed for the reflector pieces of the PBR. These reflector pieces have a $2\frac{1}{2}$-in. nominal diameter rather than a 2 in. diameter with a length of

$15\frac{3}{4}$-in. (fig. 3). The basic difference in the reflector and lattice capsules is the specimen retention washer. For the reflector capsule, two sets of specimens may be tested. One set is positioned on the large diameter next to the capsule segment wall, and another set is positioned on a smaller diameter next to the capsule-segment-subassembly tie sleeve.

From these brief descriptions of modification to the original capsule design, it is seen that the design is versatile, a desirable feature when considering standard practice for hot laboratory and reactor operations.

CAPSULE HYDRAULICS AND HANDLING

When installed in the reactor, primary cooling water enters the capsule through an opening in the plunger of the top retention piece (point 1 in fig. 7). The flow is then downward through the tubular length (1-2 and cross section A-A) of the plunger and enters a cavity (2-3 and cross section B-B) in the top retention piece. From here the water is channeled through three orifices (3-4 and cross section C-C) into the test specimen section (4-5) of the capsule assembly.

Water flow over the test specimens encounters a complex series of cross sections. The upper section of the capsule and the capsule-segment spacer disks do not contain test specimens, but do contain tie rods. The cross section shown in cross section D-D is illustrative of the capsule hydraulic cross section in these regions. The downstream flow areas are shown in the cross sections given in figure 7. Water discharges from the capsule by way of a single tubular length (5-6 and cross section J-J) in the bottom retention piece.

Reactor primary cooling water also flows through a 0.076-in. annulus between the capsule wall and the beryllium-lattice-piece wall. The water passageway in the exit region at the bottom of the lattice piece is shown by cross section K-K.

Water flow tests were conducted on this capsule assembly using a hydraulic flow loop built for testing PBR fuel elements. A schematic flow diagram of the test setup is shown in figure 10. An aluminum piece machined to the same configuration and dimension as the beryllium lattice piece was installed in the test section of the flow loop.

A capsule was loaded to near maximum capacity with tensile specimens, 1/8-in.-diameter rod specimens, and corrosion bar specimens. Flux monitor capsules were positioned in the center of the test specimen cavity. The capsule was installed in the cavity of the simulated lattice piece. The cross section at the bottom of figure 10 shows the water flow areas through the test section. Three water channels pass through the flow-loop test section, namely:

a. A water channel around the outside of the aluminum test piece;

b. A water annulus (0.076 in.) between the outer wall of the capsule assembly and the inner wall of the aluminum-test-piece cavity;

c. A water channel through the capsule assembly.

Three series of tests, the results of which are plotted in figure 11, were run on the capsule assembly. The tests were conducted with:

a. No flow channels blocked, (runs 1 and 4 in fig. 11);

b. The flow channel through the capsule sealed, other channels open (run 2 in fig. 11);

c. The flow channel through the annulus sealed, other channels open (run 3 in fig. 11).

Flows were measured as the pressure drop across the test section was increased and as it was decreased. The zone of interest, corresponding to the pressure drop across the PBR core, is around a ΔP of 40 psi.

The results of the hydraulic tests show that the flow in the annulus is about 32 gpm (difference between curves 2 and 3 at 40 psi). This flow is in agreement with the 35 gpm ±10 percent value that was found in hydraulic tests on the PBR (ref. 9, p. 16). In addition, the flow through the test section is about 10 gpm (difference between curves 2 and 4). These results indicate that the hydraulics of the reactor primary cooling water (total flow of about 18,000 gpm) are not altered appreciably by replacing the beryllium plug with the capsule assembly. The value of 10 gpm was adopted for heat-transfer calculations pertaining to in-pile operation of the capsule. In addition to these flow tests, some handling experience with the capsules has been obtained.

The handling of the capsule is rather straightforward and simple as far as reactor insertion and removal is concerned. The basic capsule has been in-pile for one reactor cycle. Removal of the capsule assembly from the reactor tank is likewise simple in that use is made of a fuel-element discharge chute built into the side of the reactor tank and discharging into the bottom of the reactor quadrant, (see fig. 2). The capsule assembly can easily be handled underwater between reactor and the hot laboratory (fig. 1). Once installed in the hot laboratory, the capsule disassembly is accomplished by removal of the three long-nosed tie screws from the side of the top-retention-piece body (fig. 4). In preneutron handling, remote disassembly and reassembly of the capsule sections have been performed in the hot cell with ease by PBR hot laboratory personnel.

A limited amount of experience (familiarity operation) has been accumulated by the PBRF staff in the disassembly and reassembly of individual capsule segment subassemblies such as shown in figure 5. On a first effort basis, hot laboratory personnel have completely disassembled the capsule segment subassembly, removed the test specimens (with tweezers), reinstalled the test specimens, and reassembled the capsule segment assembly in less than one hour.

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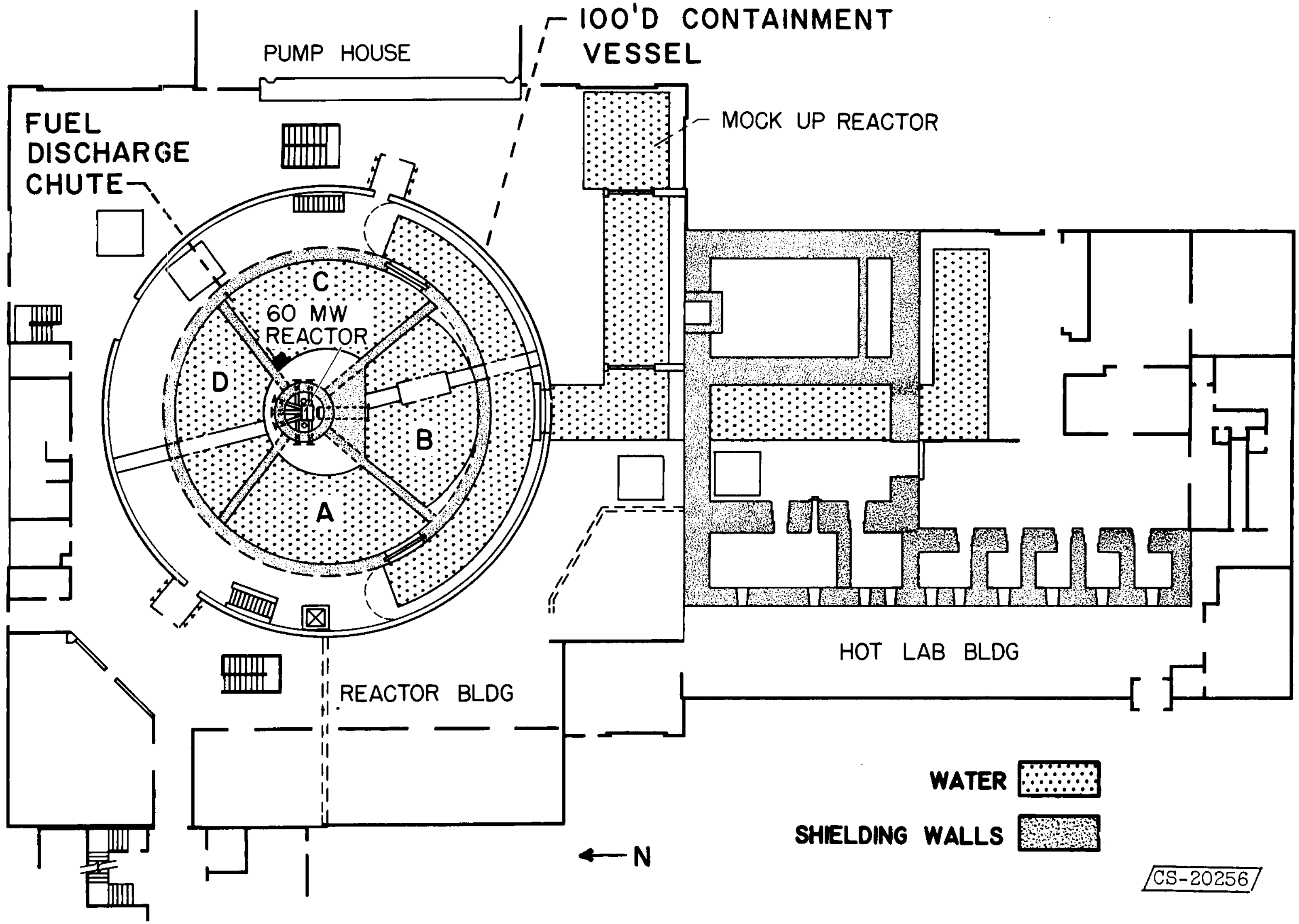

Figure 1. - Underwater transport paths.

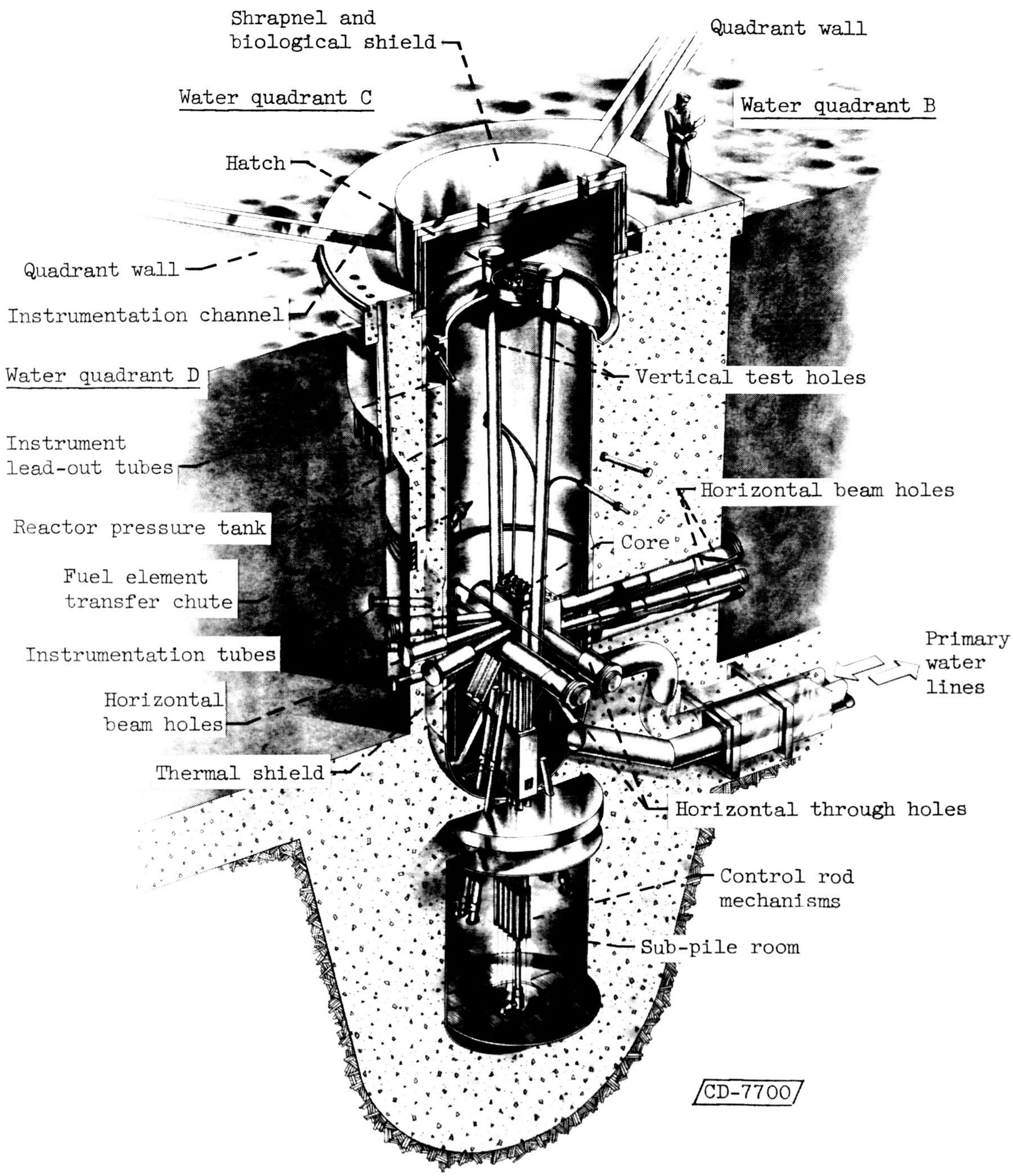

Figure 2. - Cutaway perspective drawing of reactor tank assembly.

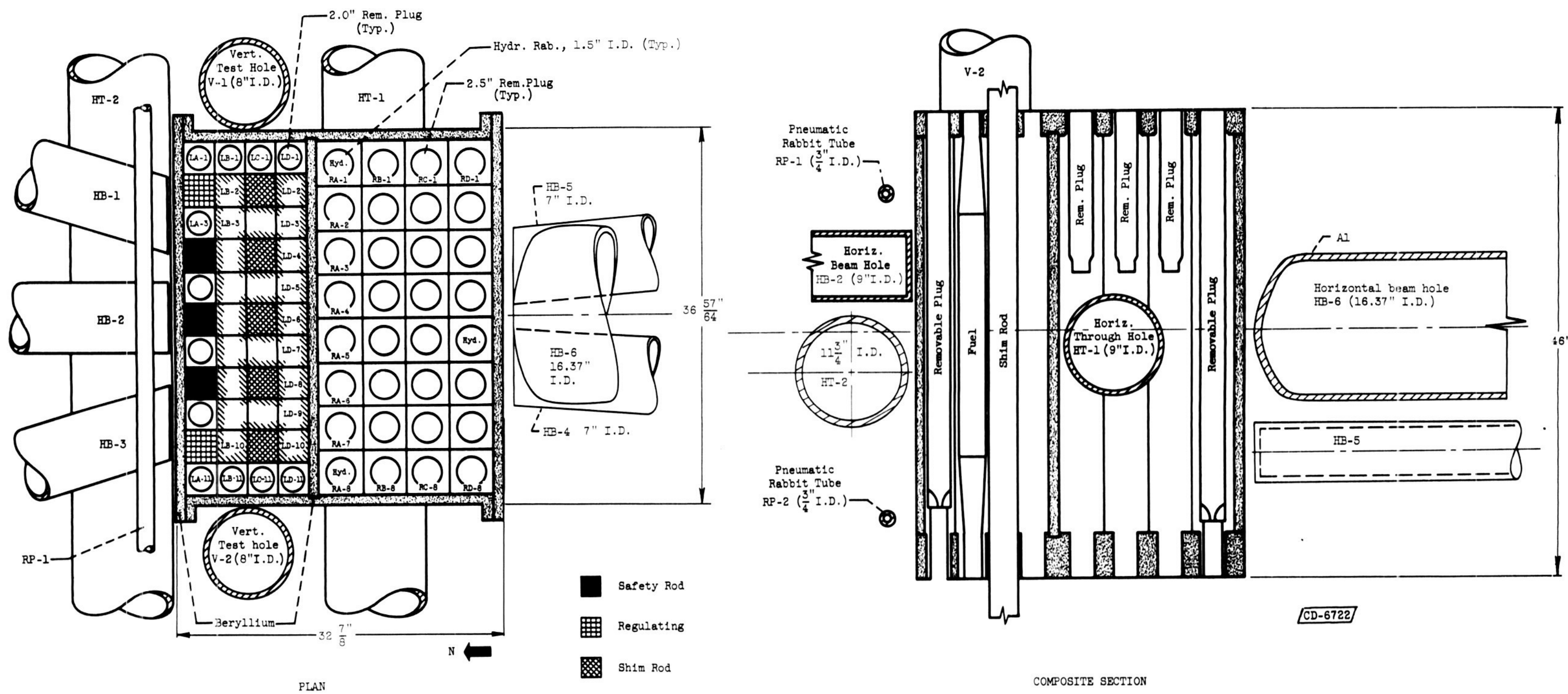

Figure 3. - Reactor core and experimental facilities.

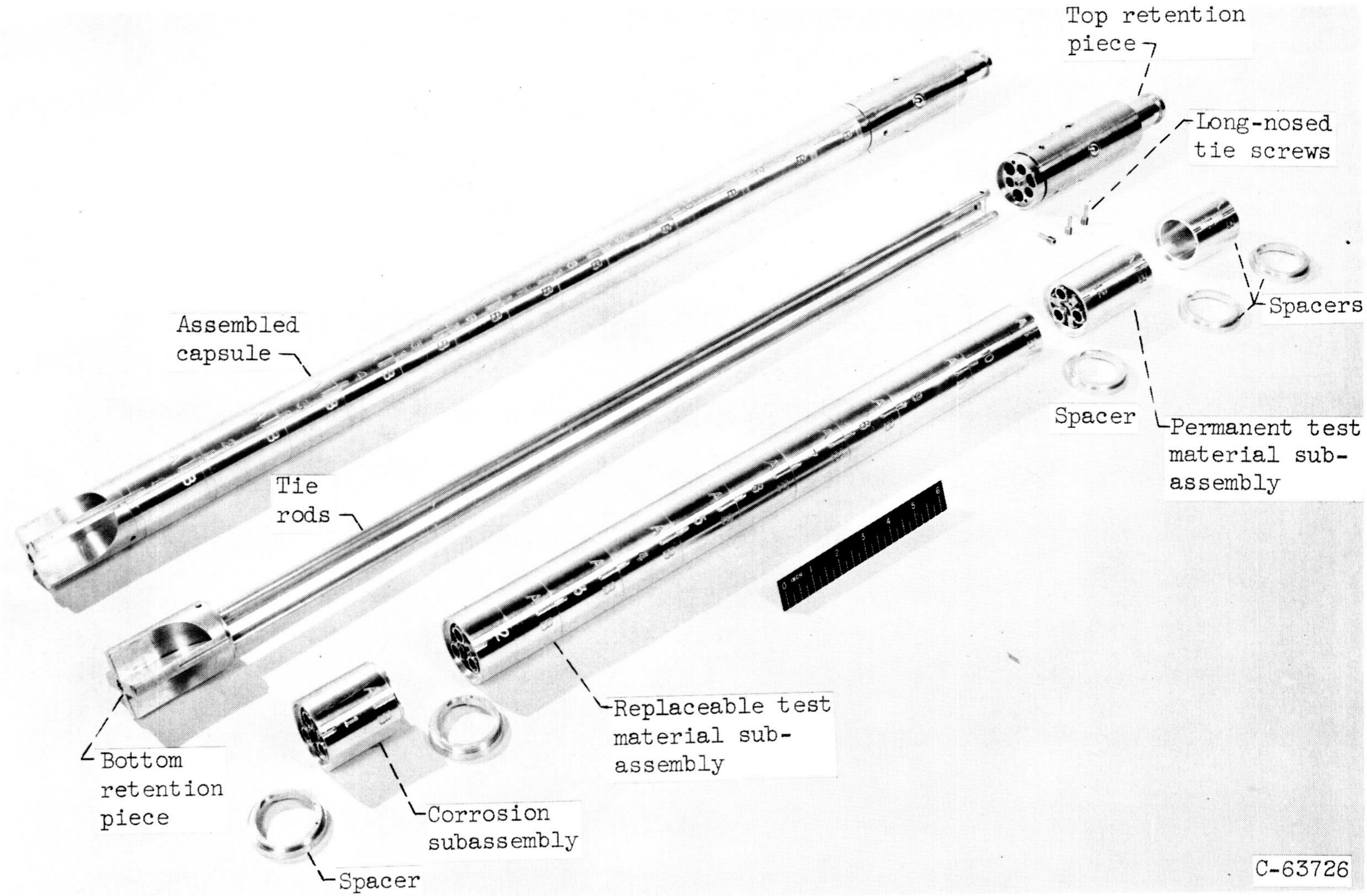

Figure 4. - Radiation capsule retention assembly.

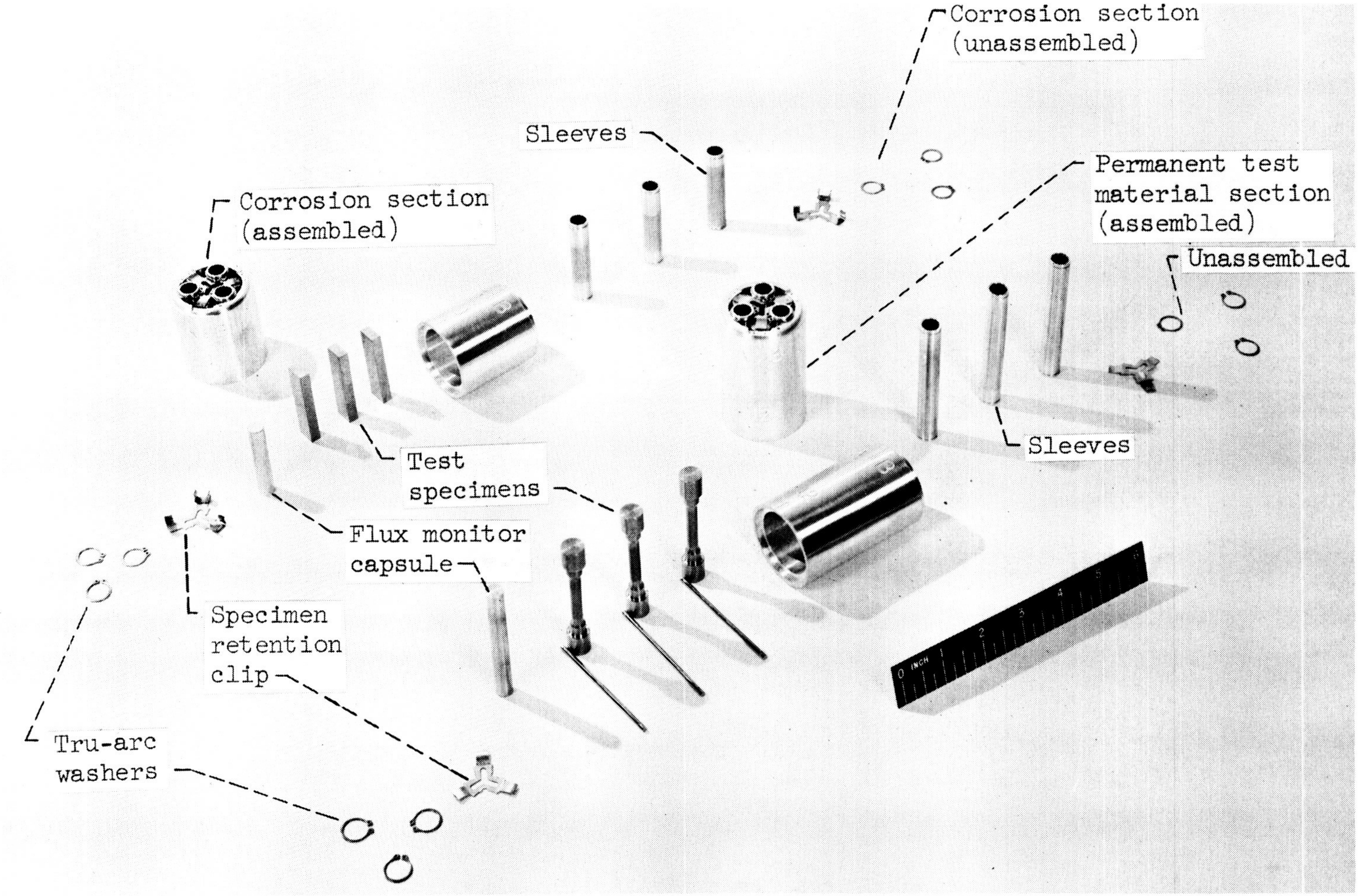

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Figure 5. - Radiation capsule, corrosion specimen subassembly and permanent test material subassembly.

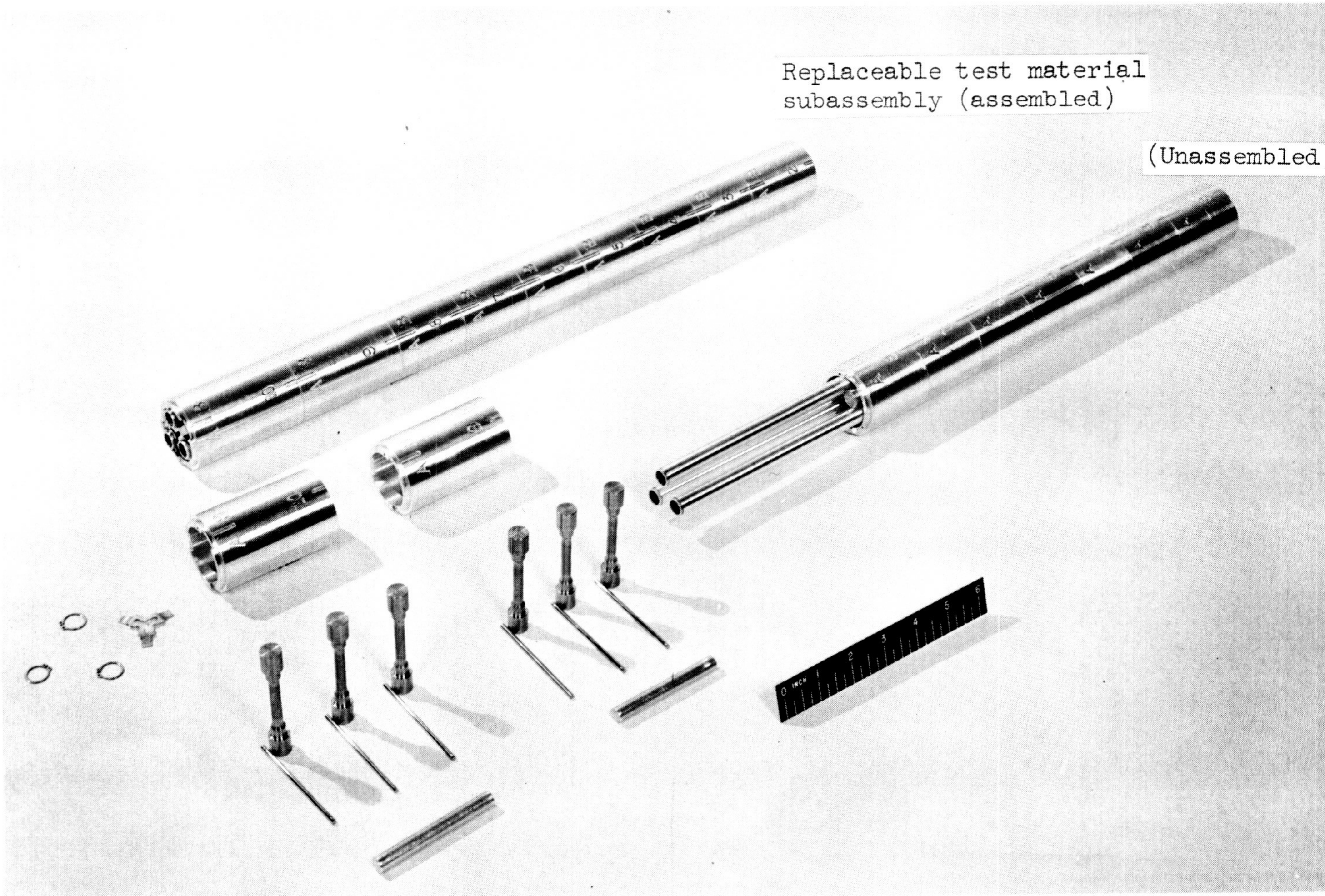

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Figure 6. - Radiation capsule, replaceable test material subassembly.

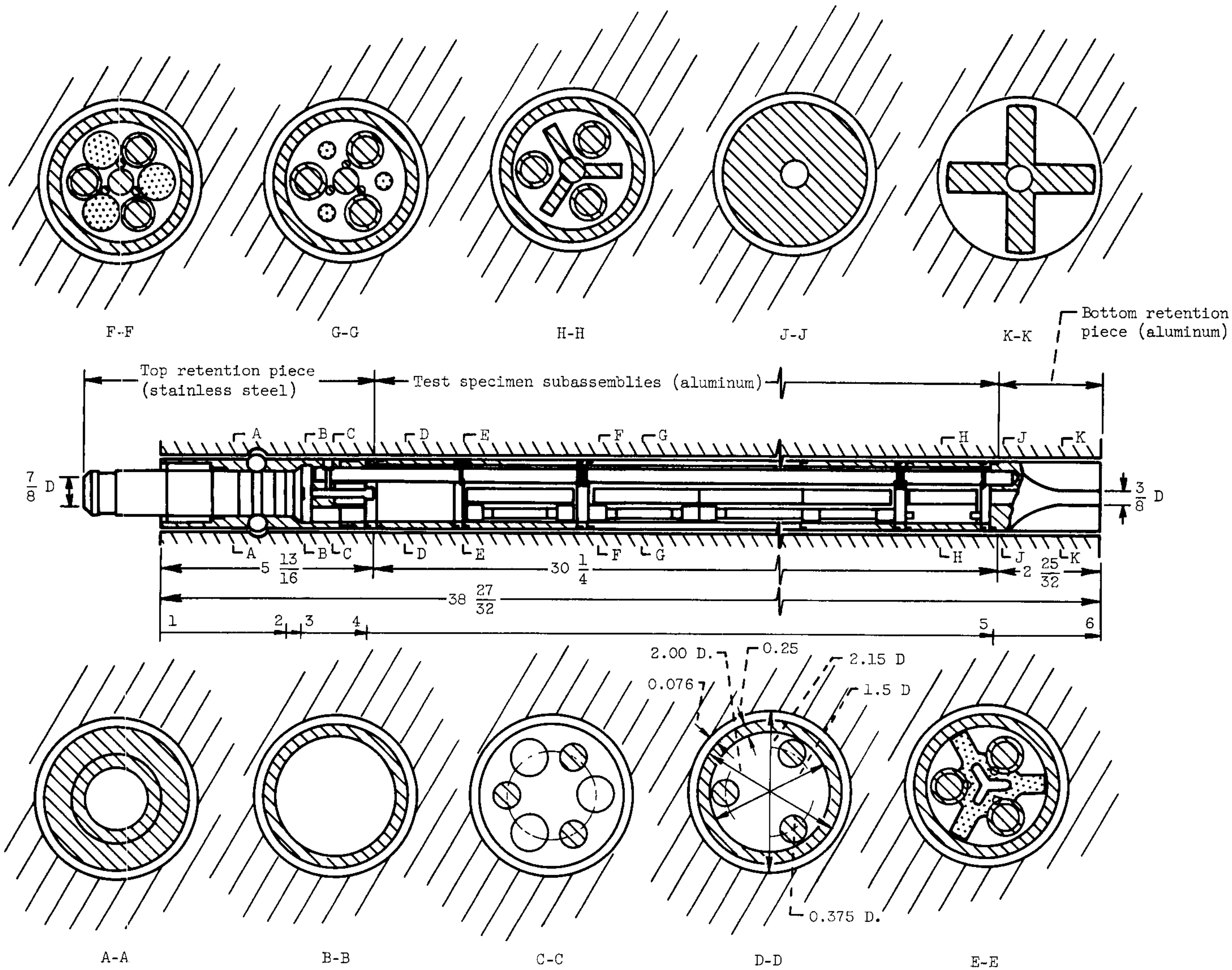
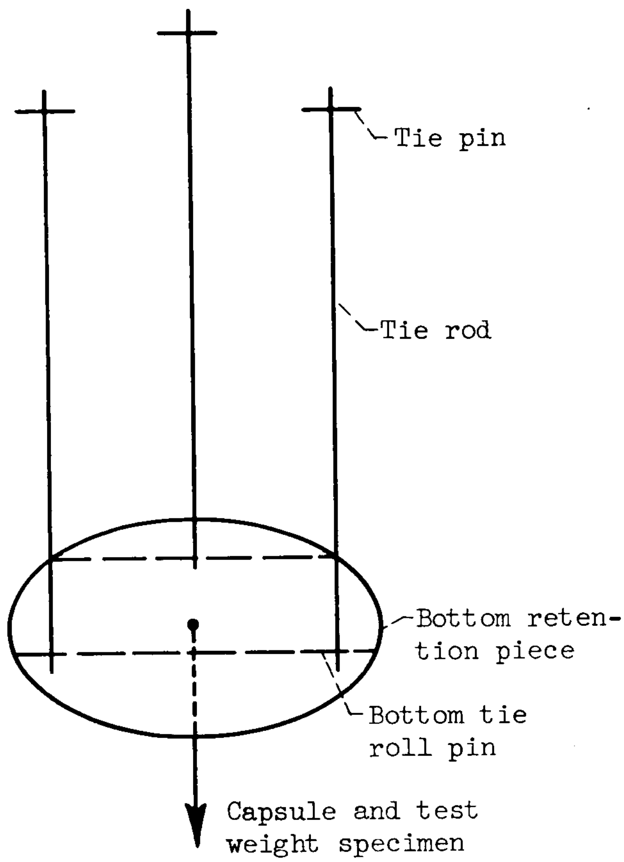
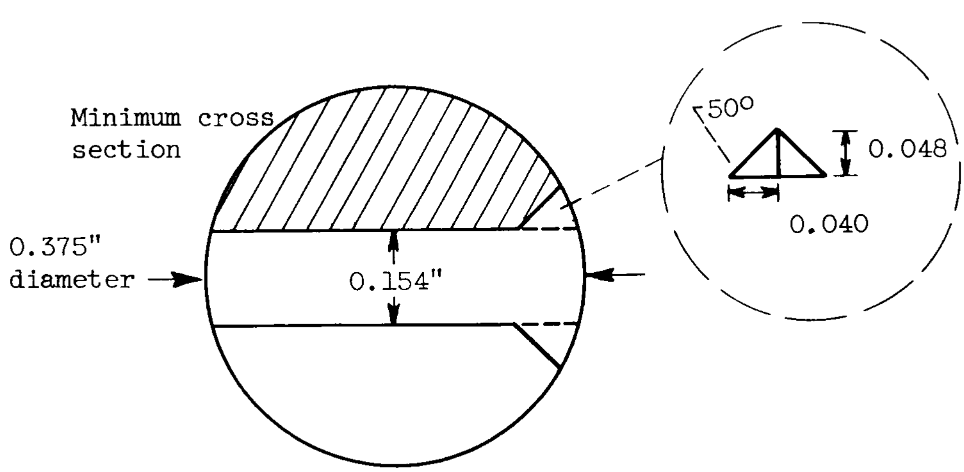


Figure 7. - Schematic of capsule assembly (waterflow area shown open).



(a) Schematic of capsule loading.



(b) Minimum cross section of capsule tie rod.

Figure 8. - Stress loading and minimum cross-sectional area of radiation capsule.

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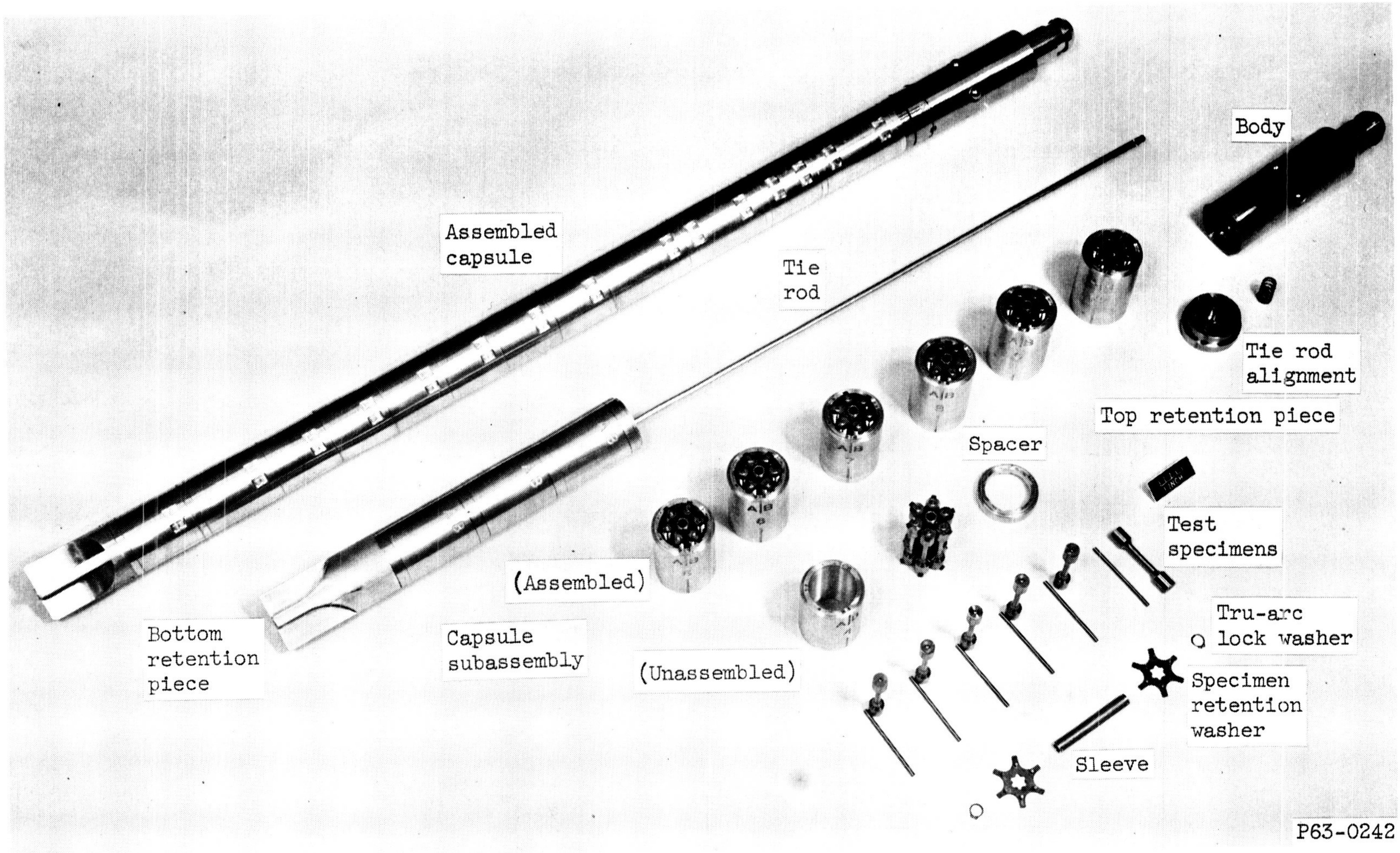

Figure 9. - Radiation capsule, modified.

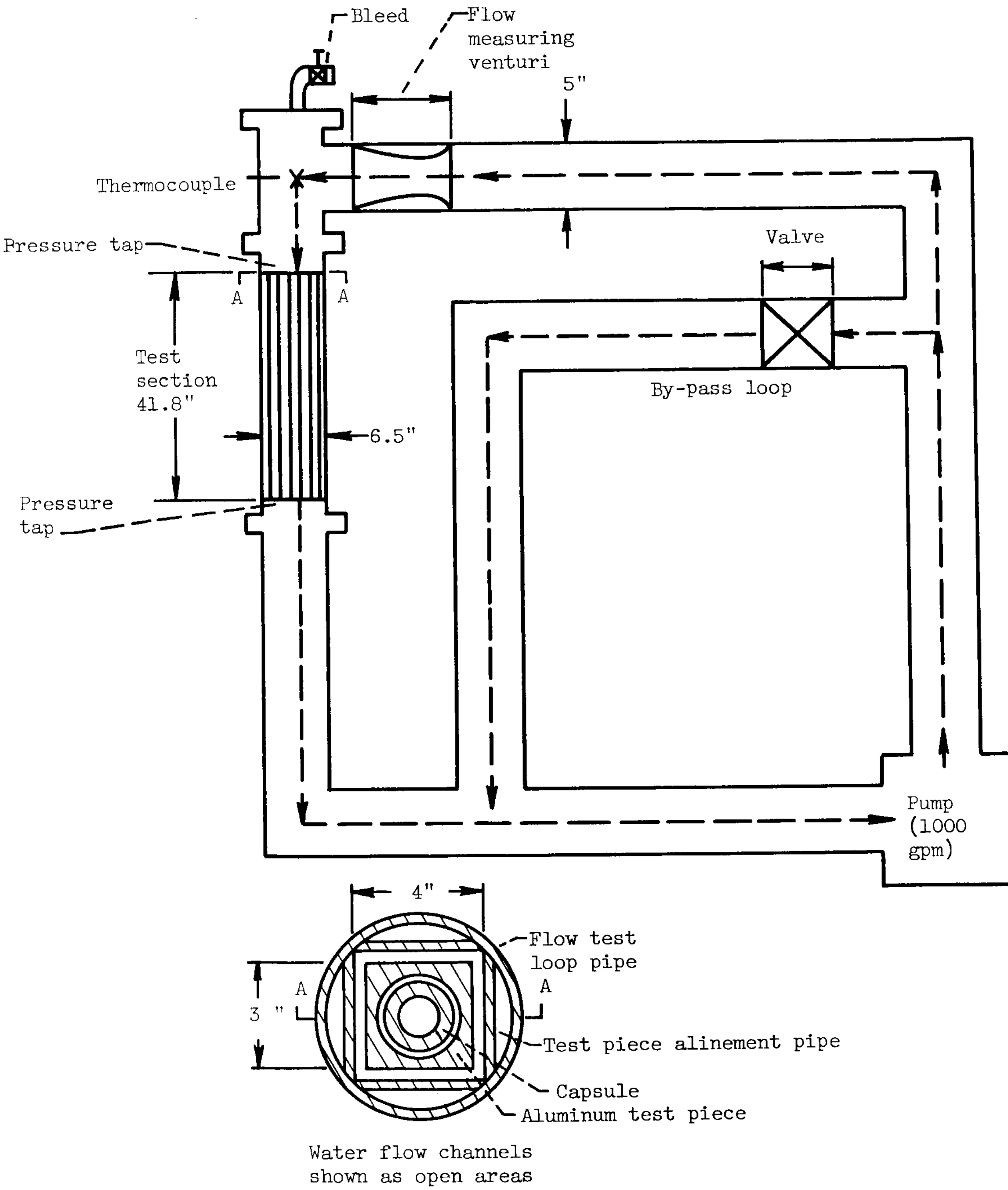

Figure 10. - Fuel element flow test loop at PBRF and capsule flow test scheme.

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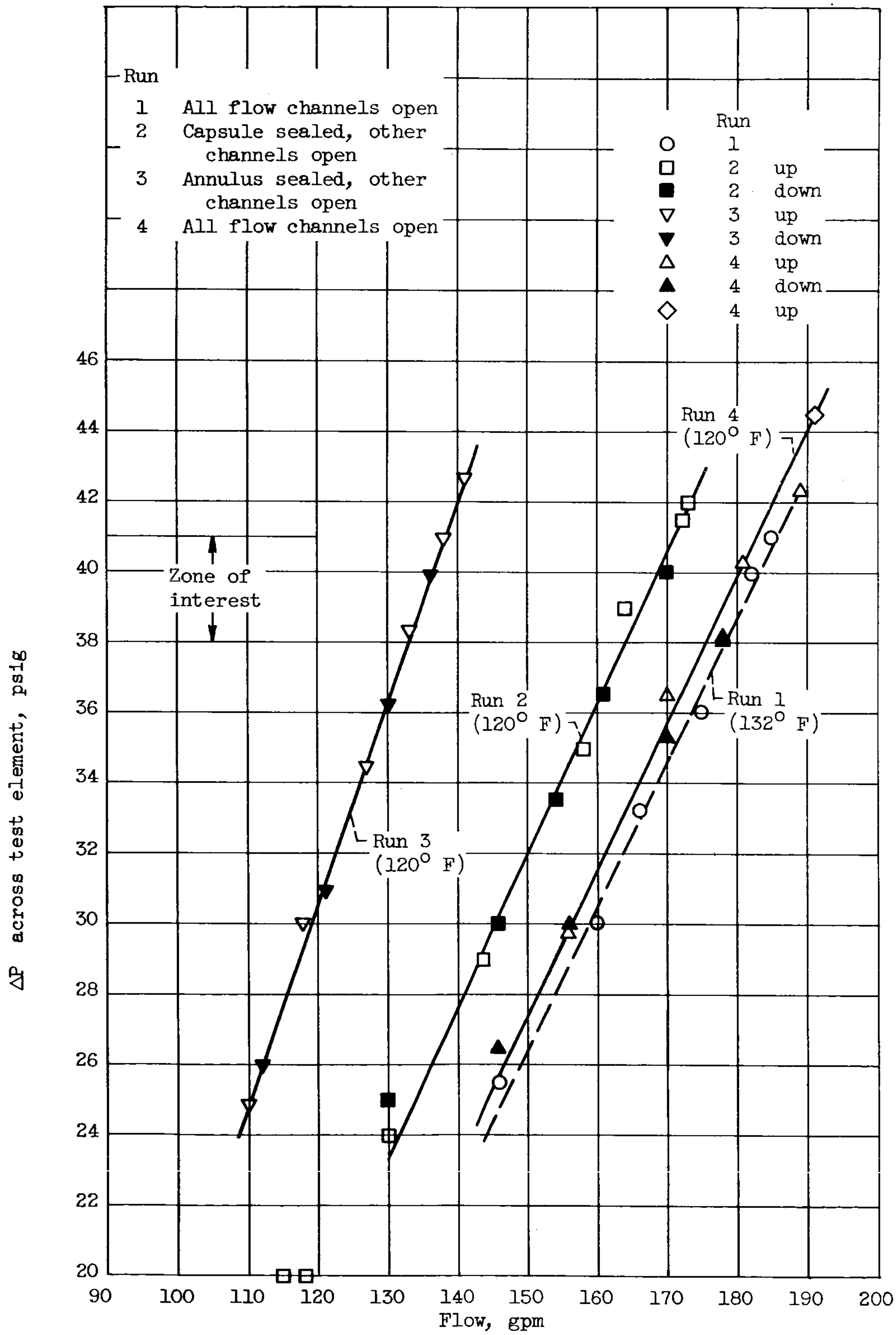

Figure 11. - Flow tests on radiation capsule.